

Galactic Cosmic Ray Origin Sites: Supernova Remnants and Superbubbles

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Abstract. We discuss processes in galactic cosmic ray (GCR) acceleration sites - supernova remnants, compact associations of young massive stars, and superbubbles. Mechanisms of efficient conversion of the mechanical power of the outflows driven by supernova shocks and fast stellar winds of young stars into magnetic fields and relativistic particles are discussed. The high efficiency of particle acceleration in the sources implies the importance of nonlinear feedback effects in a symbiotic relationship where the magnetic turbulence required to accelerate the CRs is created by the accelerated CRs themselves. Non-thermal emission produced by relativistic particles (both those confined in and those that escape from the cosmic accelerators) can be used to constrain the basic physical models of the GCR sources. High resolution X-ray synchrotron imaging, combined with GeV-TeV gamma ray spectra, is a powerful tool to probe the maximum energies of accelerated particles. Future MeV regime spectroscopy will provide unique information on the composition of accelerated particles.

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INTRODUCTION

A hundred years after the discovery of cosmic rays (CRs) there is little doubt that supernova remnants (SNRs) are the sources of the bulk population of CRs in the Galaxy with energies up to a few times 10^{15} eV (see e.g., [1, 2]) and may well produce CRs to 10^{18} eV (e.g., [3]). Diffusive shock acceleration (DSA) is the most likely mechanism to accelerate CR particles in the forward and reverse shocks of the SNR shells. The high efficiency of the DSA mechanism has been demonstrated by nonlinear modeling (see e.g., [4, 5, 6, 7, 8]). However, SNRs do not comprise a uniform population of similar objects. There is a wide variety of different SNRs since their evolution, CR acceleration, and non-thermal emission depend strongly on both the circumstellar and interstellar environments [9, 10, 11, 12, 3, 13].

It is important that a substantial fraction of core-collapsed supernovae likely occur in compact clusters of young massive stars and are associated with molecular clouds. The most massive stars explode first and their shocks are propagating through a complex environment created by both the very strong radiation of young massive stars and radiatively driven stellar winds. We discuss in §1 the results of modeling CR acceleration and the nonthermal emission of a supernova exploding in the stellar wind of its progenitor star following [14]. In addition to an isolated SNR, in a compact rich cluster of young massive stars the distances between the young stars may be about 10-15 pc and therefore

CRs may also be accelerated when the MHD flows produced by the supernova shell interact with a stellar wind from a nearby massive star. Particle acceleration in the region where the expanding supernova shell approaches a powerful stellar wind is discussed in §2 [see also 15, 16]. At a later stage of the young stellar cluster evolution (an age of about ten million years) multiple supernova explosions with great energy release in the form of shock waves inside a superbubble is a favorable site for particle acceleration. The collective acceleration from both stellar winds of massive stars and core collapsed supernovae in superbubbles was discussed in [17, 18, 19, 20].

CR ACCELERATION BY CORE-COLLAPSED SNRS

Early type stars with masses above $\sim 16M_{\odot}$ (of B0 V type and earlier) are thought to create hot, low-density bubbles with radii ~ 10 pc surrounded by a massive shell of matter swept up from the parent cloud by the stellar wind. A SN exploding in the early stages (i.e., the first few million years) of the OB association evolution would interact with a cavern created by the pre-supernova wind. In this case, a strong supernova shock propagates for a few thousand years in tenuous circumstellar matter with a velocity above 10^3 km/s before reaching the dense massive shell. Magnetic field fluctuations in the shock vicinity may be highly amplified by instabilities driven by the CR-current and CR-pressure gradient in the strong shocks [21, 22, 23]. This is an important factor for determining the highest energy particles accelerated by the shocks.

A nonlinear, spherically symmetric model of the core-collapsed SNR RX J1713.7-3946 that includes a hydrodynamic simulation of the remnant evolution coupled to the efficient production of CRs by DSA at the supernova forward shock was studied in [14] (see Figure 1). High-energy CRs that escape from the forward shock are propagated in surrounding dense material that simulates either a swept-up, pre-supernova shell or a nearby molecular cloud. The continuum emission from trapped and escaping CRs, along with the thermal X-ray emission from the shock-heated ISM behind the forward shock, integrated over the remnant, was compared against broadband observations. Overall, the GeV-TeV emission is dominated by inverse-Compton (IC) emission from CR electrons if the supernova is isolated regardless of its type, i.e., not interacting with a $\gg 100M_{\odot}$ shell or cloud. If the SNR is interacting with a much larger mass $\gtrsim 10^4M_{\odot}$, pion production by the escaping CRs may dominate the TeV emission, although a precise fit at high gamma-ray energies will depend on the still uncertain details of how the highest energy CRs are accelerated by, and escape from, the forward shock (FS). Importantly, even though CR electrons dominate the GeV-TeV emission, much more energy is put into CR ions and the efficient production of CR ions is an essential part of our leptonic model.

An important factor that allows a good fit to the broadband spectrum of SNR RX J1713.7-3946 with leptons, particularly including the highest energy HESS points, stems from the fact that the pre-SN wind magnetic field, in which the SN explodes, is considerably lower than $3\mu\text{G}$ due to the expansion of the wind. This allows the electrons to be accelerated to higher energies before radiation losses dominate. We take a pre-SN wind with speed V_{wind} , mass-loss rate dM/dt , and temperature T_{wind} , all of which are assumed constant. The parameter σ_{wind} determines the wind magnetic field at a radius R from the

explosion according to

$$B_0(R) = \frac{(\sigma_{\text{wind}} V_{\text{wind}} dM/dt)^{1/2}}{R}. \quad (1)$$

The constant parameter σ_{wind} is the ratio of magnetic field energy density to kinetic energy density in the wind and can be related to properties of the star by [e.g., 24, 25]

$$\sigma_{\text{wind}} \propto \frac{B_*^2 R_*^2}{(dM/dt) v_w} \times \left(\frac{v_r}{v_w} \right)^2. \quad (2)$$

Here, B_* denotes the surface magnetic field of the star, R_* is the stellar radius, v_r is the star rotation velocity, and $v_w = V_{\text{wind}}$ is the terminal speed of the wind. Obtaining $\sigma_{\text{wind}} \sim 0.03$ by fitting the spectrum of SNR RX J1713.7-3946, as was done in [14], constrains the progenitor star parameters. As noted by [25], values of $\sigma_{\text{wind}} \ll 1$ indicate that the stellar wind dominates the magnetic field, producing a roughly radial field far from the star.

For the parameters used in [14] [see also 26], the upstream magnetic field at the forward shock at the current age of SNR RX J1713.7-3946 is $\sim 2 \times 10^{-7}$ G and the $\sim 10 \mu\text{G}$ field immediately downstream from the shock is amplified by a factor of about 50 above the unshocked wind magnetic field (see Figure 2). The low unshocked wind field reconciles efficient CR acceleration, and the accompanying strong magnetic field amplification (MFA), with the low magnetic field that is required for leptons to produce the highest energy gamma-ray emission with IC. It may also provide the relatively wide (\sim parsec-scale size) profile of the IC emission consistent with the observed TeV profile. The discussion of the possible effect of the reverse shock can be found in [27]. We confirm that the circumstellar medium (CSM) can strongly influence the non-thermal emission from core-collapsed SN Ib/c and SNI Ib SNRs, and emphasize again that the magnetic field of the progenitor massive star may be well below the average interstellar medium (ISM) values of a few micro-Gauss alleviating an apparent contradiction between the low postshock magnetic field values required by the leptonic origin of high energy gamma-rays with the strong magnetic field amplification expected in efficient DSA.

It is also important to emphasize that, even though electrons dominate the high-energy emission, the DSA model we are discussing accelerates CR ions efficiently. The results we illustrated here (Figures 1 and 2) place 25 to 50% of the forward shock ram kinetic energy flux into relativistic ions at any instant. Only 0.25% or less of the instantaneous ram kinetic energy flux goes into relativistic electrons. Leptons dominate the model emission simply because leptons radiate far more efficiently than ions, not because ions are missing. Furthermore, the best-fit parameters for this remnant result in maximum proton energies of $\sim 10^{14}$ eV. Iron nuclei would be accelerated to $\sim 26 \times 10^{14}$ eV, well into the CR “knee” regime.

CR ACCELERATION BY COLLIDING SNR-WIND SHOCKS

The blast wave of the SNR is expected to accelerate the wind material producing ultra-relativistic ions and electrons. The highest energy CRs escape from the SNR forward

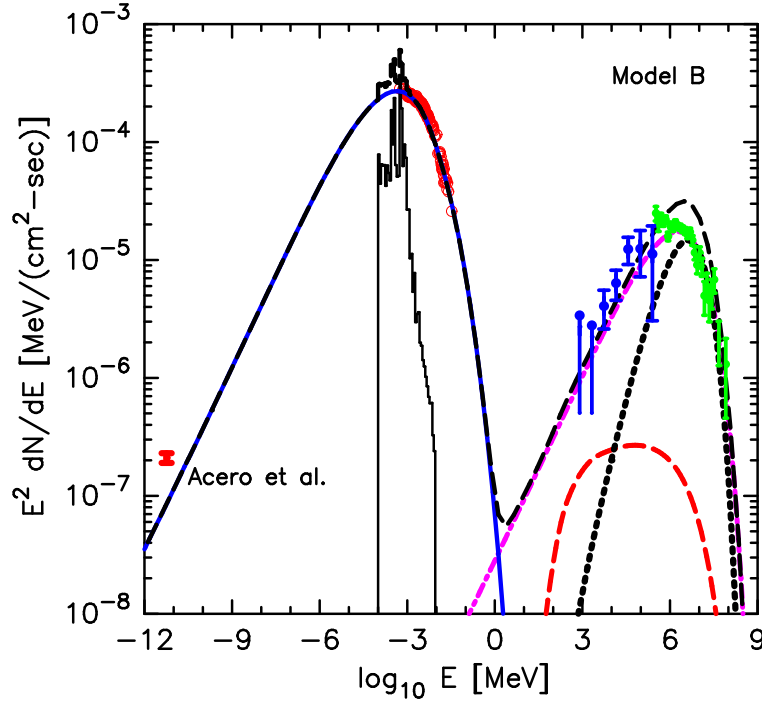


FIGURE 1. A model fit to SNR RXJ1713 observations from [14]. The different emission processes are: synchrotron (solid curve), IC (dot-dashed curve), pion from trapped CRs (dashed red curve), pion from escaping CRs (dotted curve), and thermal X-rays (solid curve with X-ray line features). The dashed black curve is the summed emission.

shock and can reach the termination shock of the stellar wind of a nearby massive star. In Figure 3 we show a highly simplified situation where the SNR shock approaches the stellar wind from a young OB-star. For efficient acceleration in such a system, the distance L_{12} between the shocks should be about a pc and we estimate that this stage may last about 1,000 yrs.

We modeled the energetic particle acceleration in the region where the expanding supernova shell is approaching a powerful stellar wind of a young massive star as it is illustrated in Figure 3. At the evolutionary stage where the mean free path of the highest energy CR is comparable to the distance between the two shocks, L_{12} , the system is characterized by a very hard spectrum of accelerated CRs as discussed in [15]. The hard CR spectrum produces unusual spectral energy distributions (SEDs) of synchrotron and IC emission as illustrated in Figure 4. The SED is derived for the moment of close approach of the shell with the stellar wind with $L_{12} \lesssim 0.1$ pc. For comparison, we show in Figure 4, with the dotted lines, the SED produced by an isolated SNR shock at a similar age.

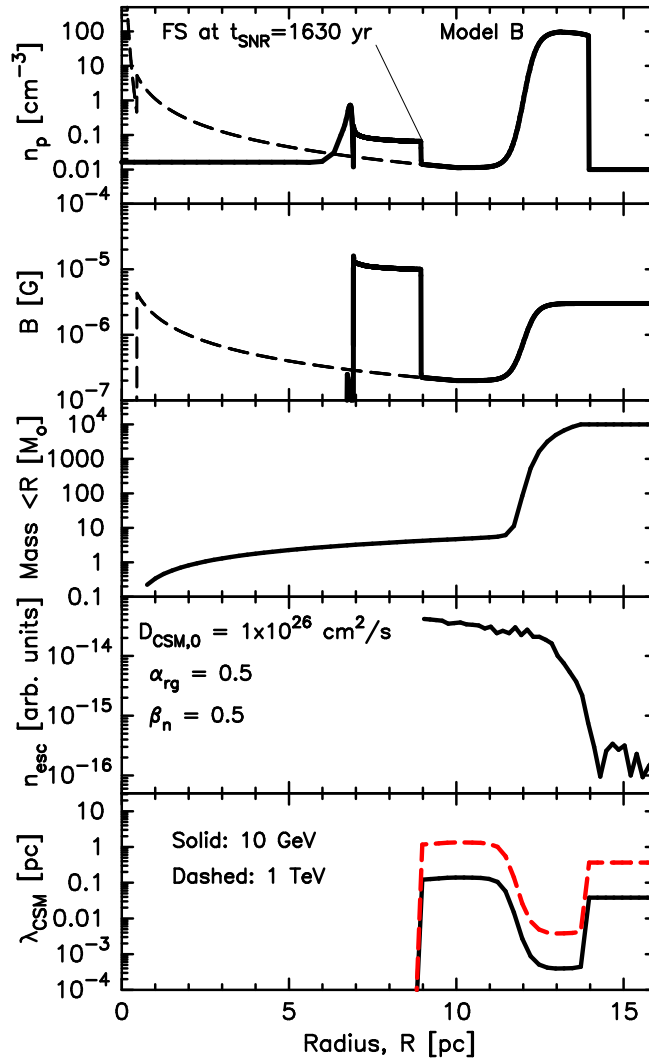


FIGURE 2. Radial profiles for SNR RX J1713.7-3946 from [14]. The top two panels show the proton number density and the magnetic field as a function of distance from the center of the SNR. In each of these two panels, the dashed curve is the profile at the beginning of the simulation and the solid curve is the profile at $t_{\text{SNR}} = 1630$ yr. The third panel shows the mass within R at $t = 0$ and the fourth panel shows the escaping CR number density. The diffusion parameters used in [14] are listed in the fifth panel. Escaping CRs are only followed beyond the FS and they leave the spherically symmetric simulation freely at the outer radius of ~ 16 pc.

The maximum CR energy

The effect of different environments in which an isolated SNR may evolve on the maximum CR energy, and the time evolution of the maximum energy, was discussed in [28]. In their model, the maximum CR energy is generally reached in the ejecta-dominated stage, much before the start of the Sedov-Taylor stage. It was concluded that, for SNe evolving within the winds of their massive stars, the maximum energy is reached very early in the evolution.

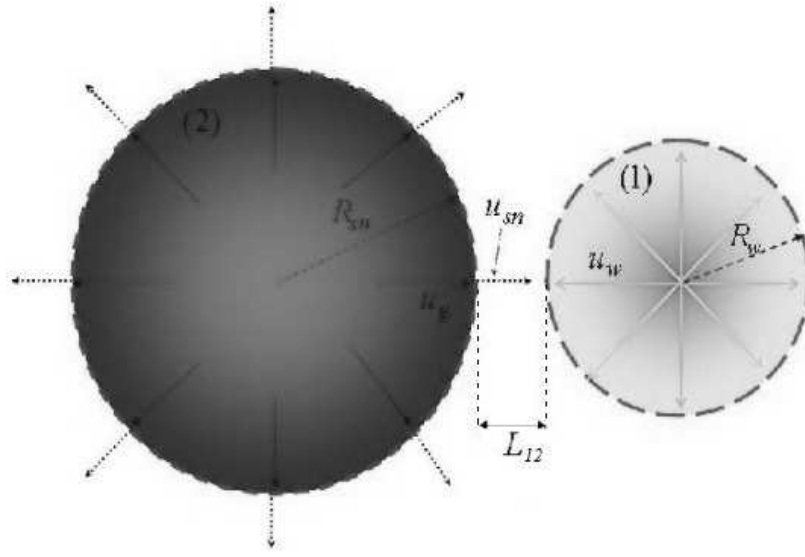


FIGURE 3. Simplified SNR–stellar wind system as described in the text. The supernova remnant is on the left and the stellar wind termination shock is on the right.

As shown in [16], a supernova exploding in a young stellar cluster and interacting with a nearby strong stellar wind will produce higher maximum energy CRs in the colliding MHD flows compared to an isolated SNR. Furthermore, the SNR can produce high-energy CRs at the Sedov-Taylor evolution stage.

The evolution of a SNR, after the star explosion, is characterized (in chronological order) by the free expansion phase, the Sedov-Taylor stage, and the radiative stage. During the free expansion phase the forward shock velocity of the ejecta is approximately constant. At the Sedov-Taylor stage, the ejecta starts to decelerate when the swept-up mass becomes comparable to the ejecta mass. The transition from the free expansion phase to the Sedov-Taylor stage occurs around the time t_{Sedov} (see e.g., [29]) where

$$t_{\text{Sedov}} = 2.6 \left(\frac{E_{\text{SN}}}{10^{51} \text{erg}} \right)^{-1/2} \left(\frac{M_{\text{ej}}}{8M_{\odot}} \right)^{5/6} \left(\frac{n_0}{0.1 \text{ cm}^{-3}} \right)^{-1/3} \text{ kyr}. \quad (3)$$

Here, n_0 is the number density of the interstellar medium, E_{SN} is the SNR explosion energy, M_{ej} is the mass of the ejecta, and M_{\odot} is the mass of the Sun.

The evolution of the forward shock radius $R_{\text{sh}}(t)$ and shock velocity $u_{\text{sh}}(t) = dR_{\text{sh}}/dt$ during the Sedov phase of the SNR expansion are given by the following equations:

$$R_{\text{sh}} = 25.5 \left(\frac{M_{\text{ej}}}{8M_{\odot}} \right)^{1/3} \left(\frac{n_0}{0.1 \text{ cm}^{-3}} \right)^{-1/5} \left(\frac{t}{t_{\text{Sedov}}} \right)^{2/5} \text{ pc}, \quad (4)$$

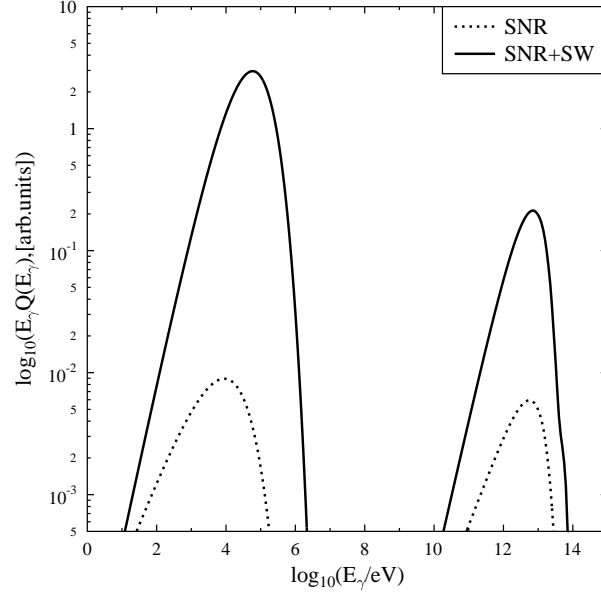


FIGURE 4. Spectral energy distributions of the synchrotron and IC emission from electrons accelerated at the colliding shock system (solid line) compared with the emission from electrons accelerated by a single isolated shock of the same speed (dotted line). The SEDs are given in arbitrary units.

$$u_{\text{sh}} = 3.7 \cdot 10^3 \left(\frac{E_{\text{SN}}}{10^{51} \text{erg}} \right)^{1/5} \left(\frac{n_0}{0.1 \text{ cm}^{-3}} \right)^{-1/5} \left(\frac{t}{t_{\text{Sedov}}} \right)^{-3/5} \text{ km s}^{-1}. \quad (5)$$

For the calculation of the maximum momentum evolution we use the approach proposed in [30]:

$$\frac{p_{\text{max}}}{m_p c} = \frac{3\chi u_{\text{sh}}(t) R_{\text{sh}}(t)}{v r_{g0}}, \quad (6)$$

where $r_{g0} = mc^2/eB_0$, $v \approx c$ is the particle velocity, $B_0 = 1 \mu\text{G}$ is the unperturbed magnetic field strength, $\chi = 0.04$, and the mass ejected with the SNR explosion is $M_{\text{ej}} = 8M_{\odot}$.

In Figure 5 we illustrate the evolution of p_{max} accelerated in the system in which the forward shock of the SNR approaches the strong stellar wind from a young OB star being at the Sedov-Taylor stage. The SNR-stellar wind collision may also occur well before the Sedov-Taylor phase depending on the compactness of the stellar cluster and inter-cluster matter distribution. At some moment during the Sedov-Taylor stage of the SNR evolution the forward shock of the SNR is close enough to the termination shock of the stellar wind to produce efficient acceleration with the sharp increase in p_{max} shown in the figure.

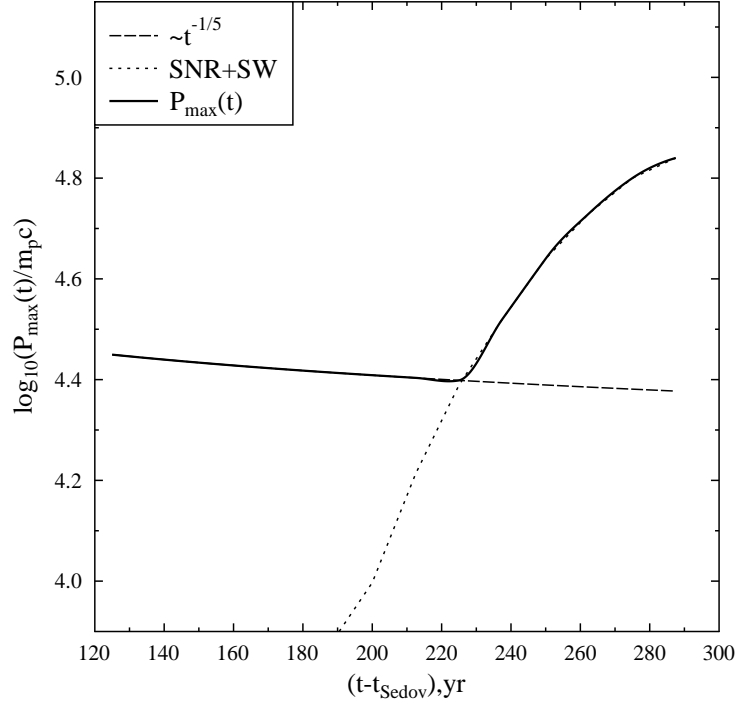


FIGURE 5. Maximum momentum of the accelerated particles in case of SNR-SW collision at the Sedov-Taylor phase of a SNR. At $t - t_{\text{Sedov}} \approx 190$ yr, particles start to be accelerated by the two-shock, SNR–stellar wind system. For this plot, t_{Sedov} is calculated from Eq.(3). The dashed curve is p_{max} for the case of ordinary SNR evolution, the dotted curve is p_{max} for the two-shock system when the SNR blast wave starts to “feel” the stellar wind of the nearest star, and the solid line is the resulting p_{max} .

The spectra of CRs accelerated in the colliding flows are harder than those from DSA produced by a single shock [15]. In the Figure 4 we compare the IC and synchrotron emission from the electrons accelerated in a colliding shock with that from electrons from a single shock. For this example, the local interstellar photon spectrum was constructed taking into account background IR fluxes typical for OB-associations, as measured by [31]. The electron distribution functions used in the spectra calculations were computed with a time-dependent model that accounts for nonlinear flow modifications in the vicinity of the shocks, and radiation losses for the electrons. It is clearly seen that the emissivity of the SNR-SW system is considerably higher than that for the single SNR shock due to the hard electron spectrum up to 10^4 GeV.

CONCLUSIONS

Supernova remnants are the most likely candidates to accelerate galactic CRs up to the knee regime and perhaps beyond the knee. Core-collapsed supernovae are thought to be statistically the dominating class of supernova events. The effect of the clustering of core-collapsed supernova progenitors, and the interaction of supernova ejecta with the circumstellar matter produced by the wind of the progenitor star, affect both the maximum energy CRs can obtain and the CR composition. In this paper we discussed briefly a few recent results illustrating the effects of both the strong wind of the progenitor massive star, and the collision of a supernova shock with the powerful wind of a nearby young massive star. In particular, we emphasized the importance of the structure of the magnetic field in the stellar wind of the progenitor star. In the case of slow rotation of the progenitor star, the wind magnetic field at large distances from the star may be well below the typical $\sim 3 \mu\text{G}$ value for the ISM. In this case, the strong SNR forward shock can accelerate CR ions efficiently with the expected strong MFA and still have low enough fields behind the shock (i.e., $\sim 10 \mu\text{G}$) so relativistic electrons can obtain high enough energies to produce the high-energy gamma-ray emission via IC before radiation losses take over.

In the case of a supernova explosion in a compact cluster of young massive stars, the collision of the supernova shock with the stellar wind of a nearby star is likely and the combined effect of shock and stellar wind may result in a substantial increase in the maximum CR energy, E_{max} . This increase in E_{max} can occur even during the stage when the maximum CR energy from the isolated SNR was declining (see Figure 5). The characteristic spectrum of non-thermal emission from the SNR-SW collision is expected to be very hard (see Figure 4), a prediction that can be tested observationally.

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